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Original Research Article

COMPARISON OF ACTUAL DEFORMATIONS OF HISTORIC WOODEN STRUCTURES WITH VALUES OBTAINED FROM STATIC CALCULATIONS

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Abstract
In historic wooden structures, deformations can be influenced by factors that are negligible within the first 50 years of the building's existence. In attics where the roof covering is made of metal sheets, the air and structural elements heat up during the day and cool down rapidly at night. This phenomenon, over a long period, can cause micro-cracks and surface material degradation. For the study, historic buildings meeting the criteria for service class II according to PN-EN 1995-1-1 were selected. Measurements of deflections, humidity, and modulus of elasticity of the wood were conducted. The actual deflections of the examined structures were found to be 28% to 37% higher than those obtained from numerical calculations, indicating ongoing rheological processes in the wooden structures.

Keywords: wooden structures, non-destructive testing, laser scanning, old timber, old wood, old timber structures, againg effect, mechanical properties assessment, timber creep

1. CHARACTERISTICS OF HISTORIC STRUCTURAL WOOD FOR TYPICAL CONDITIONS OF SERVICE CLASS II -CONDITIONS

The service life of historic buildings is very long. The strength parameters of the wooden structural elements from which the historic building is made can deteriorate over time as the wood undergoes gradual degradation due to external factors—abiotic and biotic [1]. As a result of ageing, processes such as changes in macroscopic physical properties, mechanical properties, chemical composition and microscopic structure of the cell wall occur in wood [2].

To date, numerous studies on contemporary wood have been conducted, and there is a rich scientific literature on the basis of which norms, methodologies for designing, determining, and adopting appropriate strength parameters in modern wooden structures have been developed. Scientific studies

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have rarely addressed the strength parameters of historic wood, such as modulus of elasticity or creep coefficient, which should be considered when calculating deformations in historic wooden structures. Destructive processes in the structural elements of buildings can lead to a reduction in strength parameters or their complete destruction.

In the scientific literature published so far, only in recent years have there been few and fragmentary studies on the technical parameters of historic wood and proposals for various rheological models of wood, considering the age of the structure, humidity, long-term loads, and other factors. The few studies of historic wood conducted so far have been carried out in different parts of the world. The wood analysed came from various tree species, and the studies were conducted using different methods on samples of varying sizes [3-8]. The results presented indicated the necessity of continuing research and standardising research methods to obtain unambiguous results and enable comparison. Research on wooden historic structures has been conducted in Poland [9-12], but it has only slightly covered the study of strength parameters of historic wood.

The figures (Figures 1 and 2) present the timeline and topics related to the strength parameters of historic wood discussed in the scientific literature. The data for the charts were taken from the "Scopus" database.

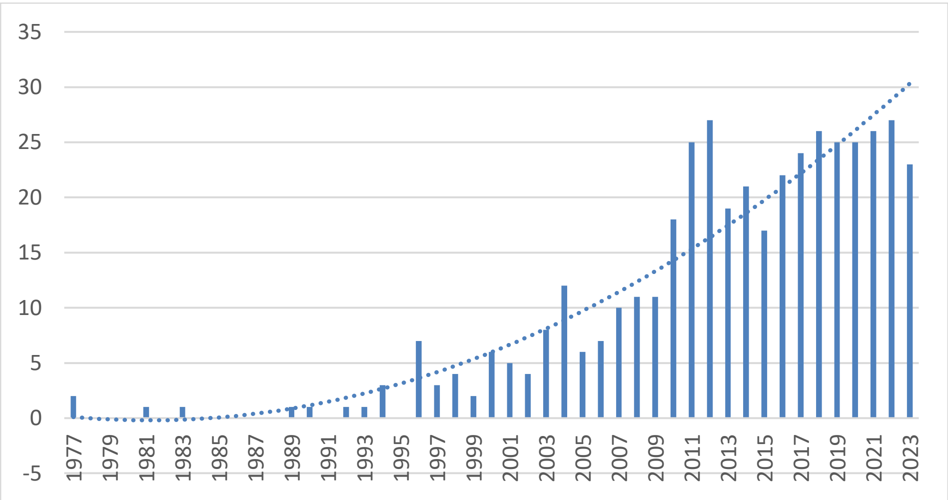

Fig. 1. Quantitative summary of publications on historic wood research (Source: own compilation based on ‘Scopus’ database)

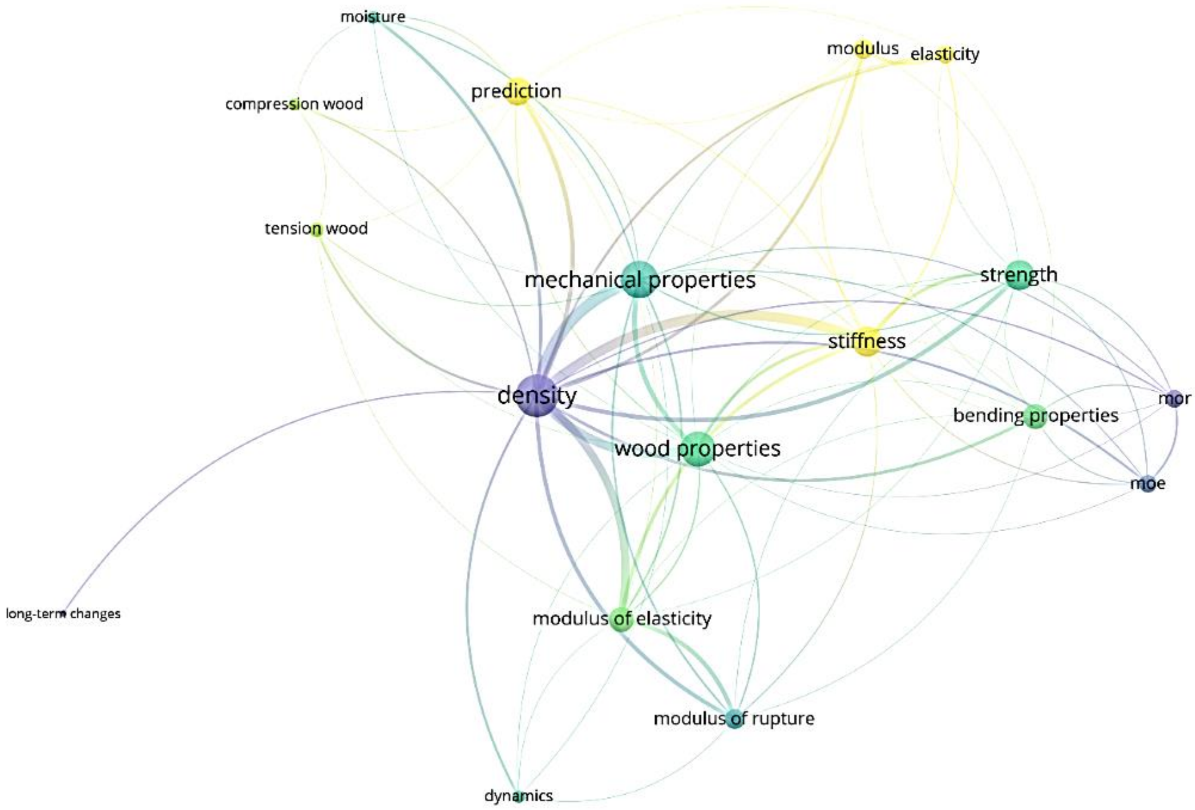

Fig. 2. Historic wood research topics conducted and published in the scientific literature (Source: own compilation based on 'Scopus' database)

Figure 1 shows that interest in the topic was low and began to increase sharply in the last twenty years. The graph (Figure 2) presents the subjects and number of scientific articles on selected physical and strength parameters of historic wood in the international scientific literature. The font and point size reflects the number of scientific papers in a given topic. The largest number of scientific articles was focused on the topic of density whereas the smallest number was devoted to the topic of changes in wood over a long period of time.

Due to the long service life of historic wooden structures, wood creep begins to be affected by factors that are negligible in the first 50 years of a structure's life. This topic is discussed in detail in paper [13], where the author indicates that the values of wood creep coefficients k_{def} contained in the standard [14] are suitable for determining the deformation of structures in the second class of service whose age does not exceed 50 years. In contrast, they may not be suitable for determining the deformation of wooden monumental structures whose age is well over half a century. Consequently, the results of deflections and displacements obtained from the calculations may underestimate the actual values. In the paper [14], the results of a study carried out in the region of south-west Germany are reported. Previously, deformation studies of existing wooden structures were also carried out and their actual values were compared with deformation results obtained from numerical calculations [15, 16]. These works indicated that the actual deformations of the investigated structures were greater than the values obtained from the calculations.

2. ANALYSIS OF ACTUAL DEFORMATIONS IN RELATION TO DEFORMATIONS OBTAINED FROM STATIC CALCULATIONS

In the case of historic buildings (where their age significantly exceeds 50 years), creep begins to be influenced by factors that are insignificant in the earlier years of the building's existence, such as:

- Ageing of the wood,
- Cyclical changes in air humidity throughout the year,
- Daily temperature fluctuations,
- Stress value.

In attics on sunny days, especially when the roof covering is made of metal sheets, the air and roof structure elements heat up during the day and cool down rapidly at night. Over a long period, this phenomenon can cause micro-cracks and surface material degradation.

Example can be the wooden trusses in historic buildings classified in service class II according to the standard [8], where the roof covering is made of metal sheets. Over a long period, they are exposed to factors that can significantly affect their strength parameters. During the annual cycle, mainly in the summer period, on sunny days, as the metal sheets heat up and there is no thermal insulation in the attic, high temperatures prevail during the day, and at night they decrease. In spring and summer, this phenomenon is cyclical. The wood's moisture content drops rapidly and can reach 12%, whereas at the end of the winter period, it can be 22%. The impact of this phenomenon, causing increased rheological influences, has been discussed, among others, in the study [13].

The issue of the influence of moisture cycling and long-term loads has been thoroughly presented in studies [13, 17-22] where rheological models of wood were proposed. These and other factors can significantly influence rheological effects in historic wooden structures classified in service class II according to the standard [8].

In the natural forest regionalization in force in Poland [23], a division into eight lands was distinguished: I Baltic, II Mazury-Podlasie, III Wielkopolska-Pomerania, IV Mazovia-Podlasie, V Silesia, VI Małopolska, VII Sudeten and VIII Karpaty. This division has proved its worth in practice, facilitating forest management in accordance with the natural character of the region. In addition, it has enabled typological studies of sites that require locating the areas under consideration in the appropriate natural and forest region, in order to determine the geological-soil and climatic conditions that shape habitat structure and species compositions of stands [24].

For the study, historic objects whose structures were made of pine wood from the Knyszyńska Forest, located in the Mazurian-Podlasie natural and forest region, were selected. The research was limited to historic wooden structures meeting the criteria for service class II according to the standard [14].

All buildings are located in wind zone I. The 18th century church is in snow zone III, 20km from the border of snow zone IV, and the other two objects are in snow zone IV. The surveyed facilities are at a maximum distance of 36km from each other, so the environmental factors affecting them are practically the same.

Geometric and deformation measurements were conducted within the framework of the study. Deflection measurements of beams were made using a geodetic total station and a terrestrial laser scanner. The moisture content of the examined structures was measured cyclically over a two-year period. At the end of the summer period, the moisture content of the examined elements in the attic was 12-13%, and at the end of the winter period, 20-22%. The analysed structures were classified into service class II according to the standard [14].

Only wooden structures that were not damaged as a result of biological corrosion and no clearances were observed in the joints that would cause additional deformation of the structure were qualified for testing. The modulus of elasticity and the class of wood from which the tested structures were made were determined using the procedure developed by author (Kamil Zimiński) for determining the modulus of elasticity of wood and wood class with the Woodtester device (non-destructive testing of wood). Static calculations were made with the DC Statik programme. This programme allows the calculation of deformations and internal forces in the analysed structures in the assigned service class, taking into account the relevant k_{def} factor and based on the final elastic modulus $E_{mean,fin}$.

According to the standard [14] in the calculations of final deformations, the value of the average final modulus of elasticity $E_{mean,fin}$ should be taken as:

$$\boldsymbol{E_{mean,fin}} = \frac{\boldsymbol{E_{mean}}}{(\mathbf{1} + k_{def})} \tag{2.1}$$

E_{mean} - average modulus of elasticity
k_{def} - coefficient reflecting the effect of creep; dependent on the service class.

The examined wooden structures were classified into service class II according to the standard [14], where k_{def} = 0,8. The deformations of the analysed structures were calculated for a quasi-permanent combination according to [25]:

$$\sum_{j\geq 1} G_{k.j} + "P" + "Q_{k,i}" + "\sum_{i>1} \Psi_{2,i} Q_{k,i} \tag{2.2}$$

where according to [25] Table A 1.1 for snow load Ψ_2=0,2 and for wind loadΨ_2=0,0.

Due to the fact that the roof covering in the examined buildings was made of metal sheets and, consequently, snow would not accumulate on the roof, deflections for the quasi-permanent combination were calculated.

2.1. Roof trusses from the turn of the 20th century

The main structural elements are wooden trusses made in single-hung construction, with cross-bracing and a discontinuous bottom chord (Fig. 3a, Fig. 3b). The discontinuity of the bottom chord is caused by the elevation of part of the ceiling in the central nave by about 1.6 m in relation to the side ceilings (Fig. 3b).

The suspended trusses (Fig. 4.) are spaced about 2.76 m apart and rest on longitudinal walls. The roof purlins rest on the trusses, and the rafters rest on the purlins. The trusses rest on the longitudinal walls via wall plates. The edge and central beams to which the ceiling is attached are made of timber with a cross-section of 23x29 cm. The lower braces with a cross-section of 23x29 cm, upper braces with a cross-section of 22x22 cm, and posts rest on the edge beams. The lower braces rest on the edge beams on one side, while on the other side, they meet the main beam and rest on the posts. The vertical and horizontal displacement of the brace and the central beam in this joint is not possible. Based on the analysis of the brace connection with the central beam and the connection of these elements with the post, it was concluded that the lower braces and central beams are not capable of transmitting tensile forces. The lower and upper braces are connected to the edge beams with face notches and additionally with rods and clamps. These connections are also not capable of transmitting tensile forces in the braces. Directly above the main beam are clamps with a cross-section of 2 x 12 x 22 cm. The clamps, upper braces, and posts are connected by bolts. The clamps are not connected to the hanger, which can move

freely relative to the clamps. The hangers are connected at the ridge with the upper braces by face notches made in the hanger. An identical connection was made between the hanger and the cross braces. The cross braces are connected to the upper braces with tenons and mortises.
On the basis of a multi-stage numerical analysis, deformations were obtained whose shape and scale of displacement coincide with the real deformations (Fig.4).

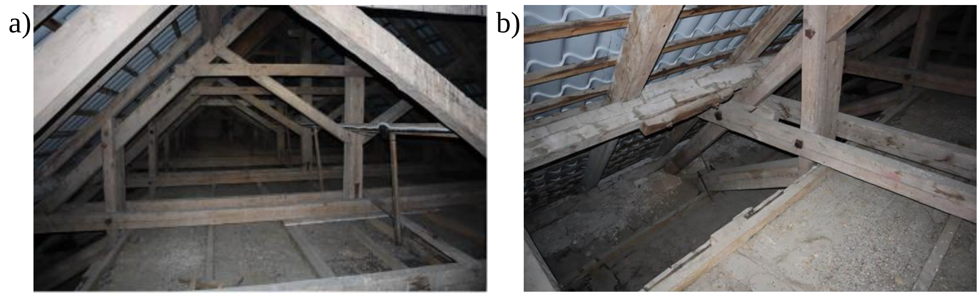

Fig. 3. View of the roof truss structure: a) over the central ceiling, b) over the side ceiling

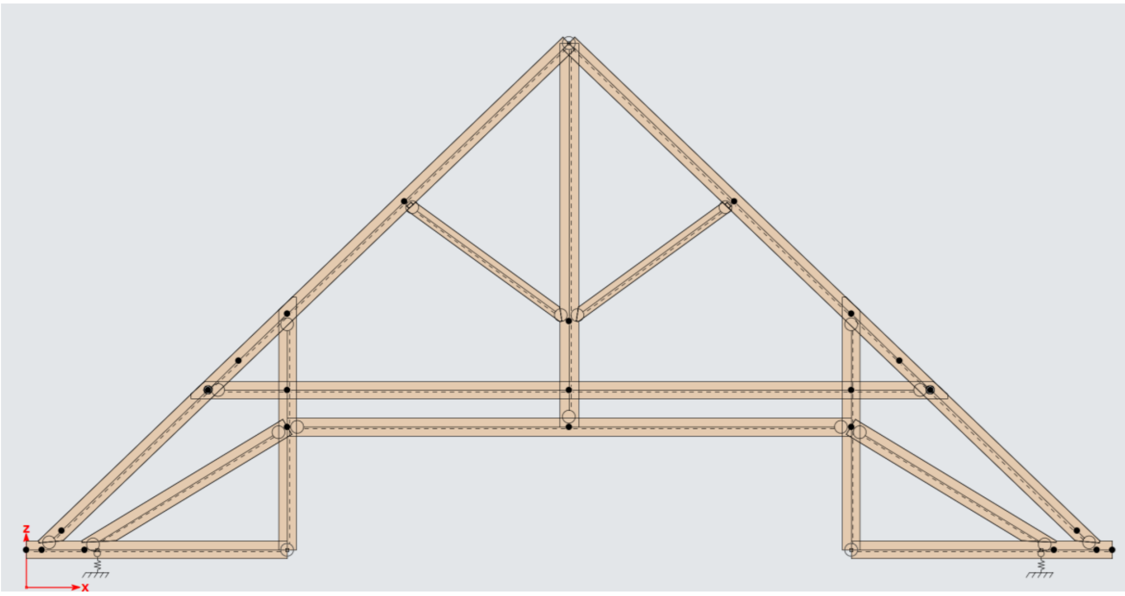

Fig. 4. Static scheme of the girder and deformation curve. When the actual static scheme is taken into account, the deformation shape coincides with the real ones

2.2. Roof truss and ceiling of the church from the second half of the 18th century

The main structural elements of the 18th century church (Fig. 5a) are the 20x25cm ceiling wooden beams resting on the longitudinal walls, which support the rafter and purlin roof trusses. The rafters and hanger are made of 16/16cm square beams, the rafters and cross-beams of 14/14cm square beams. The rafters are connected to the floor joists by a butt joint. The rafters, mayflies, cross-bracing and hangers are connected to each other with a straight cap and wooden dowels. The hangers are supported on the floor joists via a beam laid on the floor joists (Fig. 5b). The hanger connection to the floor joist is not capable of transferring tensile forces, so the roof truss is only ostensibly a hanger - the actual scheme is a rafter-collar truss.

The faulty operation of this joint was confirmed by the numerical analysis carried out and the deformation shape of the roof trusses obtained, which is consistent with the real state.
The ceiling beams support the tower (Fig. 5b), which was made in wood-frame construction. A diagram of the roof truss and floor joists can be seen in Figure 6.

a)

b)

Fig. 5. 18th century church: a) side view, b) ceiling and roof truss structure

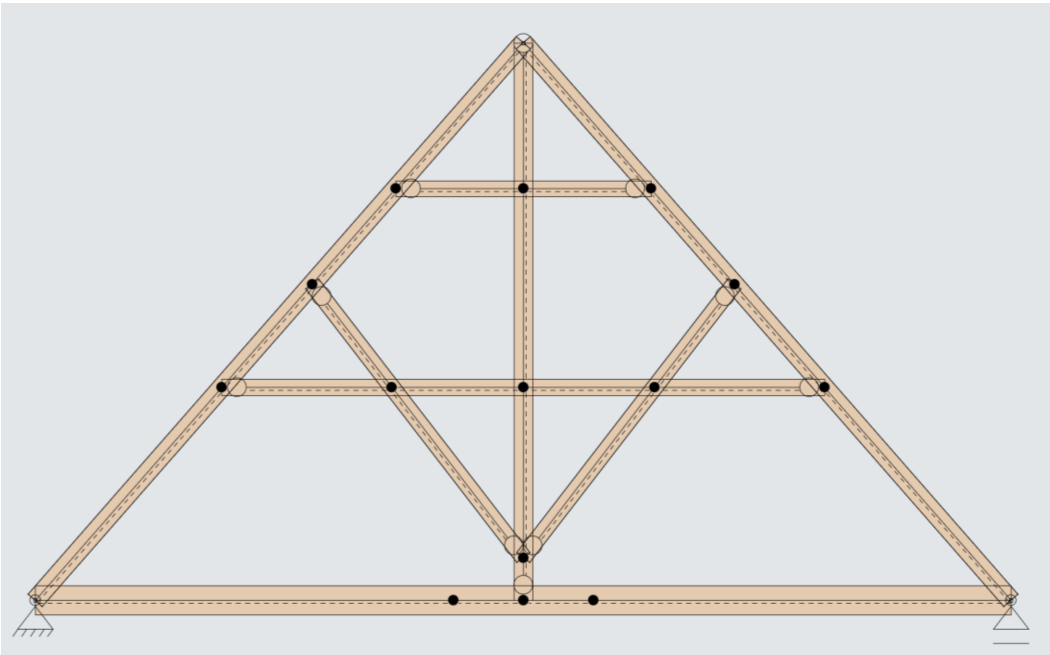

Fig. 6. Static scheme of the truss and deformation curve. The ceiling beam is not suspended from the hanger, with the result that the roof truss and the ceiling beam do not interact

2.3. Industrial building from the 19th century

The main structural elements are the 20x20cm ceiling wooden beams, which support the rafter and purlin roof trusses with rafter and purlin rafters (Fig. 7a). The rafters and centre rafter are made of 12/12cm square beams, the side rafters are made of 2x3.8/17.5cm boards. The rafters are supported on the walls by means of mullions. The rafters, are connected to each other with a straight overlap and wooden dowels. Figure 7b shows a wooden beam ceiling supported with punches. Deflection measurements were taken before the ceiling was propped.

a) b)

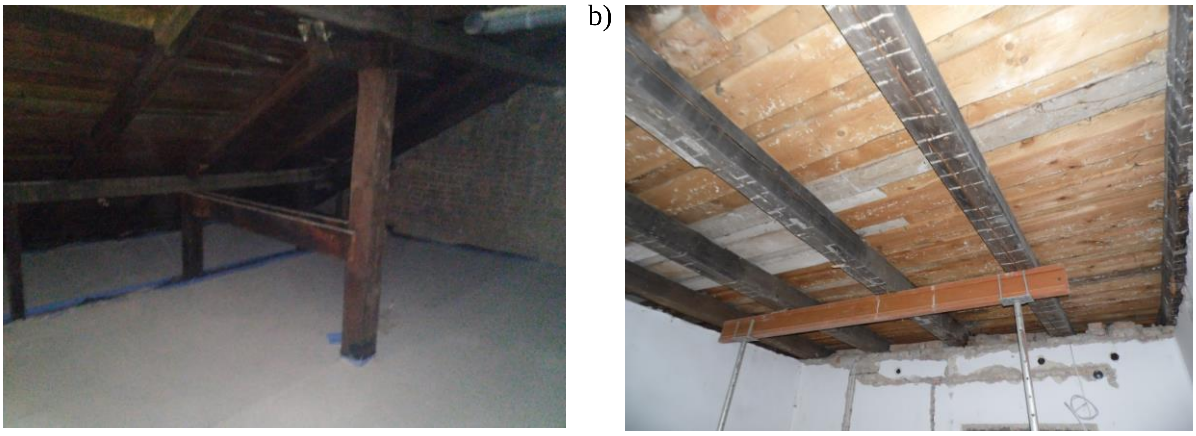

Fig. 7. 19th century industrial building: a) view of roof trusses, b) wooden beam ceiling

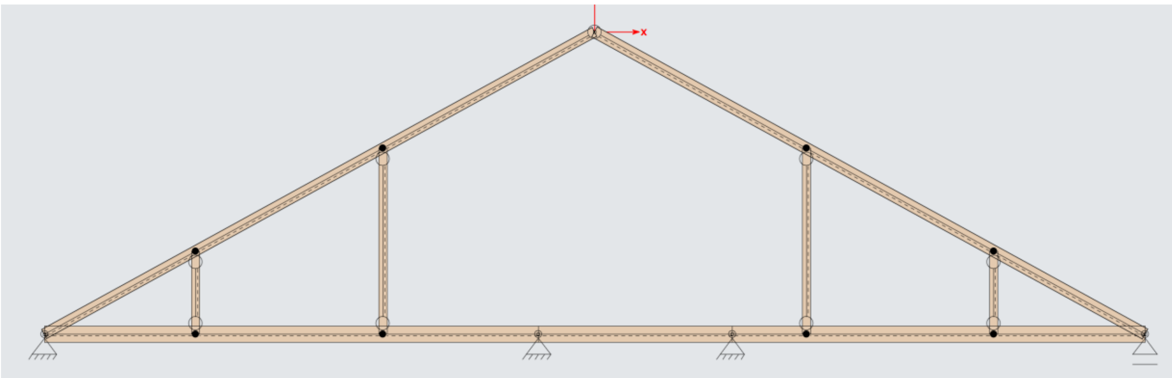

Fig. 8. Static scheme of the girder and deformation curve

Initial calculations indicated that the ceiling beams were suspended from the shear walls, which is not true (the connections of the columns to the purlins in the shear walls are not capable of transferring tensile forces). A proper static scheme was developed (it was assumed that only compressive forces could occur in the columns of the shear walls). After numerical calculations, the resulting deformation shape of the ceiling beams coincided with the actual deformations (Fig. 8).

3. RESULTS

As a result of the study, a tabular summary of the characteristics of the test structures was prepared (Table 1). The table shows the percentage differences of the actual deflections from the deflections obtained from static calculations. Column 5 summarises the k_{def} coefficient contained in the standard [14] and column 6 shows the actual k_{def} coefficient of the tested objects.

Table 1. Summary of percentage differences in actual deflections compared to deflections obtained from static calculations

1	2	3	4	5	6	7	8
Object	Difference in % between actual and calculated deflection	Roof slope angle (°)	Age of the object (in years)	kdef according to PN-EN 1995-1-1	Actual kdef	Stress value (MPa)	Mean modulus of elasticity parallel (MPa)
Roof truss from the 18th century	37	49	240	0,8	1,26	5,43	11500
Building from the 19th century	31	29	130	0,8	1,19	7,24	12000
Roof truss from the turn of the 19th/20th century	28,5	44	124	0,8	1,16	5,97	11000

The compiled deflections (Table 1), obtained from static calculations and actual deflections, show that the actual deflections are significantly higher: from 28.5% to 37% for the quasi-quasi-permanent combination and permanent loads. It should be noted that the deformations were measured during the period when the tested structures were not loaded with snow.

According to the standard [14], the final deflection value is determined by the k_{def} coefficient. The research shows that in wooden structures classified in the second class of service and whose age exceeds 100 years, the value of the k_{def} coefficient: for the quasi-quasi-permanent combination is between 1.16 and 1.26.

4. DISCUSSION

According to standard [14], the final deflection value is determined by the k_{def} coefficient. The study shows that in wooden structures classified in the second class of use and whose age exceeds 100 years, the values of the actual deflections are significantly higher compared to the values obtained from static calculations and based on the value of the k_{def} coefficient provided in the standard [14]. Similar conclusions were reported in [13, 29], where studies were carried out examining wooden-framed structures in south-west Germany. However, the objects studied were much younger (their age ranged between 31 and 40 years). In [13], it is indicated that the creep factor for a permanent load, constant moisture content of 10% and an edge stress of 13.2 N/mm2, after 50 years, calculated according to the model proposed by [26], is 1.13 and according to the model of [27] is 1.04 .

In the scientific literature, information can be found [13] indicating that the kdef coefficient for structures in the second class of use is appropriate for the design of contemporary structures, where the service life does not exceed 50 years. However, it may be too low for structures that are significantly older than 50 years. This is because the factors affecting rheological deformations in the early period of the structure's use are small enough to be negligible but can have a significant impact on increasing the creep coefficient in later periods.

The potential influence of changes in the modulus of elasticity due to the ageing of wood should be excluded, as most studies have not observed such a phenomenon [4, 5, 7, 28].

The authors of studies [30-32] indicate that mechanosorptive creep and the type of stresses significantly influence long-term creep, and these factors should be considered when determining the creep coefficient.

5. CONCLUSION

The obtained results for actual deflections differ significantly from the values obtained from static calculations and are greater by 28.5% to 37%. The k_{def} coefficient for the quasi-permanent combination, which only takes into account permanent loads, ranges from 1.16 to 1.26, unlike the standard [14] value of k_{def} = 0.8. This may indicate that rheological processes are still ongoing in the examined structures. The cyclical changes in wood moisture content, combined with the rapid heating of metal roof coverings in the summer over a long period (in historic buildings classified in the second class of use), may affect the reduction of wood's strength parameters and rheological processes.

Further research is proposed on the deformations of historic wooden structures classified in second class of use according to [14], to compare actual deformations with those obtained from static calculations and potentially calibrate the k_{def} coefficient. Based on the collected data, it will be possible to create and calibrate a rheological model that takes into account the factors influencing the rheological deformations of wooden structures over 50 years old, which will allow the determination of the k_{def} coefficient.

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